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Development of Human Posture Simulation Method for Assessing Posture Angles and Spinal Loads

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Abstract

Video-based posture analysis employing a biomechanical model is gaining a growing popularity for ergonomic assessments. A human posture simulation method of estimating multiple body postural angles and spinal loads from a video record was developed to expedite ergonomic assessments. The method was evaluated by a repeated measures study design with three trunk flexion levels, two lift asymmetry levels, three viewing angles and three trial repetitions as experimental factors. The study comprised two phases evaluating the accuracy of simulating self and other people's lifting posture via a proxy of a computer-generated humanoid. The mean values of the accuracy of simulating self and humanoid postures were 12° and 15°, respectively. The repeatability of the method for the same lifting condition was excellent (~2°). The least simulation error was associated with side viewing angle. The estimated back compressive force and moment, calculated by a three dimensional biomechanical model, exhibited a range of 5% underestimation. The posture simulation method enables researchers to simultaneously quantify body posture angles and spinal loading variables with accuracy and precision comparable to on-screen posture matching methods.

Keywords

Manual Lifting; Human Posture Simulation; Three Dimensional Static Strength Prediction Program; Biomechanical Model; Observational Method

INTRODUCTION

As indicated by several review studies summarizing a significant relationship between poor working posture and the development of musculoskeletal disorders (MSDs) (Bernard *et al*. 1997; Ferguson & Marras, 1997; Hoogendoorn *et al.* 1999, National Research Council, 2001; da Costa et al., 2010), body posture has been a main focus of ergonomic assessments. In particular, trunk flexion and twisting/asymmetry have been demonstrated to be significant risk factors for low back disorders (LBDs) (Punnett et al., 1991; Marras et al., 1995; Hoogendoorn et al., 2000; Jorgenson et al., 2003). In most epidemiological studies, working posture is typically recorded by self-administered questionnaire or pencil/paper

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observational methods (Burdorf, 1992; Li & Buckle, 1999). Due to the nature of the methods, assessments of body posture have been mostly described in gross categorical terms, resulting in relatively moderate associations with LBDs (Marras et al., 2010). Misclassification of the gross terms as physical risk factors for LBDs raise questions about their validity and relationship with LBDs (Punnett & Wegman, 2004). Epidemiological evidence associated with LBDs may be identified when the physical risk factors are properly addressed by biomechanical factors, such as the load location and weight magnitude relative to the worker and three dimensional movements during lifting (Burdorf, 1992; National Research Council, 2001; Sutherland et al. 2008; Marras et al., 2010; Boda, et al., 2010).

In lieu of field-friendly direct-reading measurement methods for body posture, computerized video-based posture analysis has been favored by many researchers as a practical alternative (Keyserling, 1986; Yen & Radwin, 1995; Callaghan et al., 2001; Bao et al., 2007). The validity of a video-based posture analysis primarily depends on the assessed body angle (Ericson, 1991; Genaidy, 1993; Burt & Punnett, 1999; Lowe, 2004; Lau et al., 2010; Bao et al., 2011; Lu et al., 2011; Xu et al., 2011) and posture viewing angle (Bao et al., 2011; Lu et al., 2009, 2011; Xu et al., 2011). The main advantage of this analysis method is minimal disruption to workers' job performance during field surveillance with a permanent record for future analyses at a very low cost (Genaidy, 1993; Li & Bukle, 1999; Bao, 2011). Recorded posture or movement data can be further used for biomechanical modeling (i.e. inverse dynamics) to obtain joint loading variables (Chaffin 1969; Kromodihardjo & Mital. 1986; de Looze at al., 1992; Kingma et al., 1996) and cumulative spinal loads (Kumar, 1990; Norman et al, 1998; Jager et al., 2000; Callaghan et al., 2001; Sutherland et al., 2008; Lu et al., 2011). However, quantifications of cumulative spinal loading variables involve laborious manual mannequin/stick figure manipulation or manual screen digitization of body joints to match the posture on the computer screen, which is time consuming and prone to errors (Liu et al., 1997; Callaghan et al., 2001; Lu et al., 2011). It was found that it could take 11 min to manipulate the posture on the computer screen to match a working posture in a photograph (Chaffin, 1997).

To expedite this biomechanical modeling process, we developed a human posture simulation method that could simultaneously estimate multiple body posture angles from field recorded video (Waters et al., 2011). The biomechanical model used in this method was the University of Michigan 3-dimensional static strength prediction program (3DSSPP) (Garg & Chaffin, 1975; Chaffin et al. 1999). Using anthropometry, hand load, and posture data, this biomechanical model has the capability of predicting spinal compressive force acting at the L4/L5 intervertebral disc for a static working posture in the three dimensional directions (Chaffin, 1969; Chaffin & Baker, 1970; Garg & Chaffin, 1975; Chaffin & Erig, 1991). The model has been widely used in many studies as design criteria for manual materials handling jobs or a risk assessment tool for LBDs (Chaffin, 1997; Waters et al. 1998, Lavender et al. 1999; Marras et al., 1999; Garg & Kapellusch 2009).

This paper describes the development of this human posture simulation method with a goal to answer the following research questions:

1. Can human subjects simulate or mimic their own and others' posture accurately and precisely?
2. How efficient is the human posture simulation method?
3. How accurate is the human posture simulation method in estimating the back compressive force and moment in the lumbosacral region?

2. METHODS

2.1. Description of human posture simulation

The human posture simulation method we developed involved acquisition of body posture data with an electromagnetic motion capture system (Ascension Flock of Birds MotionStar® with Motion Monitor software, Innovative Sport Training Inc., Chicago, 2003). The system was calibrated and adjusted to minimize metal distortion in an approximately 3×3×3 m working space on a raised wooden platform. Thirteen sensors were attached to various body segments to track whole body movement. The sensors' anatomical locations included back of skull, thoracic vertebrae 1, lumbar vertebrae 1, left and right deltoid tuberosity of humerus, dorsal radius, mid anterior femur, mid anterior border of tibia, intermediate cuneiforms. Each sensor measured 2.5 × 2.5 × 2 cm, and was placed in a plastic pocket attached to a Velcro strap. The Velcro straps were securely wrapped around the anatomical locations to protect the sensors from motion artifacts. The cables connected to the sensors were also securely wrapped around the body segments to eliminate any tension that might cause motion artifacts. The body position and orientation data for each posed working posture were collected with the system. The data collection sampling rate and duration for each trial were set at 45 Hz and 3 seconds, respectively. Detailed information on the procedure and steps for using the human posture simulation method is described in a previous paper (Waters *et al.* 2011).

2.2. Calibration and accuracy of data collection system

The calibration method involved manually measuring a variety of positions in the working environment and comparing them to manual measurements using an anthropometer. A 2.4 × 2.4 m computer generated grid paper with grid spacing of 0.2 m was used to precisely lay out the marked calibration points in x and y directions on the platform. The numbers of the calibration points in x, y and z directions in the working environment were 11, 12 and 10, respectively, which resulted in a total of 1,320 calibration points for testing the accuracy of the measurement system. An anthropometer was used to locate the actual position and orientation of the calibration points. A sensor was securely positioned on a 7.5 × 7.5 cm square of plexiglass that was used as a mounting surface to the anthropometer for adjustments of various heights (i.e. z direction) for the calibration points. Two line levels were attached to the surface of the plexiglass to assure that the sensor was level in both x and y directions while taking measurements. A linear regression analysis was performed to calculate the root mean square (RMS) values between the measured x, y and z coordinates and the actual calibration points. The mean of the RMS values (i.e. average accuracy value) for position data in x, y and z was 1.05 cm. The mean of the RMS values for the three orientations of the sensor rotating around x, y and z axes was 0.3°(Lu et al., 2011).

2.3. Overview of the study

To answer the research questions previously mentioned in the introduction section, two phases of experiments were conducted. Phase 1 experiment was to investigate the accuracy of estimating subjects' own posture angles of 6 lifting activities using the human posture simulation method, while Phase 2 experiment was to assess the accuracy of estimating other people's posture of the same lifting activities via computer-generated mannequins as a proxy. In phase 2 experiment, the compressive force and total moment at the L4/L5 intervertebral disc for the lifting activities were also calculated for comparisons using the 3DSSPP. Moreover, the efficiency of the human posture simulation method was evaluated by a comparison with an on-screen posture estimation method in Phase 2. Detailed description of the experiments follows.

2.4. Phase 1 experiment

Eight healthy subjects (3 females, 5 males) within the Greater Cincinnati, Ohio area, were recruited to participate in the accuracy test for the human posture simulation. The means and standard deviations of their age, height and weight were 36±11 years, 174.6±9.5 cm and 75.8±13.4 kg, respectively. The consent documents signed by the subjects were reviewed and approved by the NIOSH human subjects review board. Prior to posture simulation, the subjects were informed of the risks involving simulation. They also received a training session for simulating a variety of postures to assure that they were able to simulate postures themselves in confidence. The training is documented in a previous paper (Waters et al., 2011)

The experimental design for the phase 1 experiment employed a 6 × 3 × 3 within-subject design with posture, viewing angle and trial repetition as experimental factors. The three viewing angles of each posture consisted of front (frontal view), rear (180° from frontal view) and side (sagittal view) views. Six two-handed lifting tasks were selected from recorded video in a previous field surveillance study to cover a range of vertical height and horizontal distances as well as various levels of trunk flexion (0–75°) and lift asymmetry (0 and 45°). For trunk flexion angle greater than 60°, these realistically recorded lifting postures inadvertently excluded 60° angle with 45° lift asymmetry. It was a natural choice to select a 75° trunk flexion angle that approximated 60° for comparisons. The characteristics of the six postures are presented in Table 1.

The subjects reviewed the six postures projected approximately full-scale onto a large screen (1.5 × 2.1 m) about three meters in front of them. They were asked to pose and match the postures as accurately as possible. These posed postures were photographed approximately at each subject's shoulder height from the back, front and side viewing angles, resulting in 18 reference views. The subjects' assumed postures were measured with the motion capture system and used as reference postures for evaluating the accuracy of simulating self-posture, which was conducted in a separate simulation session.

The separate simulation session was performed one week after the initial session for posing the reference postures to avoid learning effects. In the separate session, the 18 reference postures were simulated 3 times, resulting in a total of 54 trials. During each trial, the subjects were asked to pose and match one of the 54 randomly presented postures as accurately as possible. Once each posture was posed by the subjects in confidence (signaled by an audio cue from them), the computer operator started data collection. The subjects were asked to maintain the posture until data collection was completed.

2.5. Phase 2 experiment

The testing and consent procedure for the phase 2 experiment was almost identical to that for the phase 1 experiment, except the reference postures. In the phase 2 experiment, the reference postures (Table 1) were created using the built-in mannequin in the 50th percentile male body size in the 3DSSPP software as a proxy for the simulated persons. Five healthy subjects (3 females, 2 males) within the National Institute for Occupational Safety and Health (NIOSH) were recruited to participate in the experiment. The means and standard deviations of the subject's age, height and weight were 33.8±10.2 years, 171.6±7.9 cm and 70.4±8.1 kg, respectively. Similar to the phase 1 experiment, a total of 54 trials were assigned in a random order to the subjects during a separate simulation session.

2.6 Efficiency of the posture simulation method

The efficiency of the posture simulation method was evaluated by a comparison between the time spent on each simulation trial collected during the phase 2 experiment and time spent on manual posture specification on the computer screen for the same test condition. One male university graduate student (separated from the recruited subjects) in the ergonomics field was used to estimate the 15 body angles of photographed postures of one male subject from Phase 2 experiment. The student used the 3DSSPP software program to estimate the body angles on the computer screen. Similar to the simulation trials, the 54 photographed postures was given to the student in a random order to avoid any learning effect during posture specification on the computer screen. The starting and ending times for the posture specification on the computer screen were recorded manually by the student. The time spent on each simulation trial was recorded by the internal clock of the computer used for the posture data collection. All five subjects' simulation data were used for the comparison.

2.7 Posture data and validation measures

The posture data acquired from the data collection system were processed and calculated with the Motion Monitor software program to determine the 15 body angles (trunk flexion, trunk lateral bending, trunk axial rotation, left and right upper arm vertical and horizontal angles, left and right lower arm vertical and horizontal angles, left and right upper and lower leg vertical angles) defined by the 3DSSPP (The Regents of University of Michigan, 2001). The mean values of the body angles over the 3-second trial period were calculated as the posture data for each trial and used in the statistical analysis. The subjects' calculated posture data during the phase 1 and 2 experiments were compared with the reference posture data and mannequin's posture data, respectively. The absolute value of the difference was used as the accuracy measure (i.e. simulation error) for each body angle. The mean of the 15 posture simulation errors was used as the average posture simulation error and used in statistical comparisons. The choice of using the absolute difference was primarily based on the comparability with existing data in the literature (Liu *et al.* 1997). For evaluating the repeatability or precision of the human posture simulation method, the standard deviation of the three trials for the same test condition was used as the precision measure.

2.8 Back compressive force and total moment

To further assess the accuracy of the posture simulation method in predicting biomechanical measures, back compression force at the L4/L5 intervertebral disc and the total moment at the L5/S1 were used. The total moment was the resultant moment of the moment data in the x, y, and z directions. Calculations of the two biomechanical measures require not only posture data, but also hand force, direction of the force and some anthropometric data. To control for the effects of the non-posture variables, the 50th percentile male anthropometric data and three hypothetical levels of hand load (1.8, 14.6 and 27.2 kg) equally distributed to each hand in the downward direction (i.e. lifting) were used.

2.9 Statistical analyses

A repeated measures analysis of variance (ANOVA) was employed to investigate the effects of trunk flexion, lift asymmetry and viewing angle on simulation accuracy for both Phase 1 and 2 experiments. Five dependent variables were used respectively for the ANOVA including the average simulation error of the 15 body angles, three trunk posture variables (trunk flexion, lateral bending and axial rotation) and the precision measure. For generation of a balanced ANOVA, trunk flexion and lift asymmetry were grouped into three (see Table 1, A: postures 1 and 2; B: postures 3 and 4; C: postures 5 and 6) and two (Yes: postures 1, 4 and 6; No: postures 2, 3 and 5) groups, respectively. Within-subject variables, including three levels of trunk flexion, two levels of lift asymmetry and three levels of viewing angle, were used as the independent variables in the ANOVA models. Post hoc Fisher's least-significant-difference test ($p<0.05$) was performed to determine the effects of the within-subjects variables. The mean value of the three repeated trials for each test condition was used as the data element of the ANOVA models to increase the accuracy of each test condition. The posture variables were log-transformed to achieve a proximate normality for ANOVAs. The ANOVA models are expressed in the following mathematical form.

$$X_{mijkl}=\mu_m+\alpha_{mi}+\beta_{mj}+\gamma_{mk}+\varepsilon_{mijkl}$$

Where

X_{mijkl}: randomly selected data element l in the test population for targeted dependent variable m (average simulation error, trunk lateral bending error, trunk flexion error, and trunk axial rotation, or average precision measure) for 5 separate models

μ_m: grand mean of the test population for targeted variable m

α_{mi}: effect of trunk flexion group (i=3) - μ_m

β_{mj}: effect of lift asymmetry (j=2) - μ_m

γ_{mk}: effect of viewing angle (k=3) - μ_m

ε_{mijkl}: experimental error for targeted variable m

To assess the correlation between simulation- and mannequin-based back compressive force/moment, a linear regression analysis was performed. The Personal Statistical Analysis Software (SAS) version 9.1 (SAS Institute Inc, Cary, NC) was used for all the statistical analyses.

3 RESULTS

3.1. Accuracy of simulating self postures (Phase 1 experiment)

The mean and standard deviation of the average posture simulation error across all different test conditions were about 12° and 5°. Table 2 shows the ANOVA results for the two significant main effects for the phase 1 experiment. As compared to the rear and front viewing angles, the side viewing angle resulted in a statistically significant but small decrease (1–2°) in the average posture simulation error. The viewing angles, however, did not significantly affect the simulation errors for estimating trunk flexion, trunk lateral bending and trunk axial rotation angles. As compared with two other trunk flexion groups B and C (flexion<30°), trunk flexion group A (flexion>60°) caused a significant increase in the average posture simulation error and trunk lateral bending error by approximately 5° and 7°, respectively. The mean of the precision measure for posture simulation across all test conditions was 2.2°. This small precision measure indicates that the subjects appeared to be capable of simulating the same posture repetitively without generating a large posture variation.

3.2. Accuracy of simulating mannequin postures (Phase 2 experiment)

Table 3 shows the ANOVA results for the phase 2 experiment. The mean and standard deviation of the overall posture simulation error across all test conditions were about 15° and 5°. Both viewing angle and simulated trunk flexion group had a statistically significant effect on the average posture simulation error. Simulating the neutral trunk posture (group C) resulted in the least amount of error (12.8°), as compared with those for simulating trunk flexion angles 30°, 60° and 75° (i.e. groups A and B). Among the three viewing angles, the side viewing angle caused the least amount of error (13.6°). The neutral trunk angle (group C) resulted in the least trunk lateral bending error (4.1°) and trunk flexion error, as compared with the two other trunk flexion angle groups. Conversely, the trunk flexion angle group > 60° (group A) caused the least trunk axial rotation error. The mean of the precision measure for simulating the mannequin postures across all test conditions were 1.8°. This finding supports the excellent repeatability of human posture simulation found in the phase 1 experiment.

3.3. Correlation between simulation and mannequin back compressive force and moment data

To demonstrate the variation of the accuracy of estimating back compressive force and moment with simulation data in different test conditions, one subject's data were shown in Figure 1. A linear regression equation for predicting back compressive force (Figure 1 a) and moment (Figure 1b) using the simulation data was constructed, respectively. The regression coefficients for compressive force and moment were about 0.96 and 0.98, respectively. The high R-square values (0.93 and 0.88 for back compressive and moment, respectively) suggest the variances of the prediction models were explained well by this subject's simulation data. The remaining subjects exhibited a comparably good predictability. For back compressive force, their regression coefficient ranged from 0.95–1.1 with a R-square value varying from 0.82–0.93. Similarly for moment, their regression coefficient ranged from 0.96–1.0 with a R-square value varying from 0.8–0.9. The findings indicate an excellent estimation of back compressive force and moment using the human posture simulation method for a wide range of lifting postures.

Table 4 summarizes the mean values of the correlation coefficients (r's) for the back compressive force and moment across the subjects as a function of the three levels of viewing angle and hand load. In each specific test condition, the correlation coefficient ranged from 0.6 to 0.95. The grand mean of the r's for the test conditions was 0.82. As the level of hand load increased, the correlation decreased. The side viewing angle had the strongest correlation (r=0.9), as compared with the rear and front viewing angles. Similarly, the correlation of the moment between simulation and mannequin data demonstrated the same trend as the back compressive force with the same grand mean value of r=0.82.

3.4. Efficiency of human posture simulation method

The efficiency of the human posture simulation method in comparison with the manual posture specification on the computer screen is shown in Figure 2. On average, the time required for completing the manual posture specification was about 4 times longer than simulating both self and mannequin postures. The human posture simulation method clearly demonstrated a significant advantage in time saving over the manual posture specification method.

4. DISCUSSION

To validate the posture simulation method, we started with the best case scenario by simulating the subjects' self postures followed by simulating computer-generated mannequin postures as a proxy for other people's postures. Finally, the posture simulation errors and some non-posture variables (i.e. hand load and 50^{th} percentile male anthropometrics) were taken into account and evaluated together during the estimation of the back compressive force and moment.

Findings from the two phases of this study suggest that humans have a great potential for simulating their own and other people's posture with reasonable accuracy and precision. The subjects demonstrated an average 12° error for simulating their own posture and an average 15° error for simulating mannequin postures for the same variety of postures in different viewing angles. The small ~2° mean value of the precision measure from both experiments indicates that an excellent repeatability of the posture simulation method for simulating the same working condition, which agrees with the majority of the observational methods for posture specification (Takala et al., 2010). In a study using a manual observational method to estimate the same body angles for 3DSSPP, the average posture specification error (calculated with the same method used in the present study) for a similar setting (i.e. one photograph) was about 9° (Liu et al., 1997). It is difficult to have a direct comparison in the posture specification errors between the current study and Liu's study, which involved four different working postures of four different university students. We conducted a mini study to allow a direct comparison between the observation and posture simulation methods.

In the mini study (Lu et al., 2009), the simulators' self photographed postures were presented to five certified professional ergonomists for specifying the trunk flexion angle on a computer screen. Results showed that the average errors in simulating and manually specifying the trunk flexion angle were about 6° and 13°, respectively. This previous study also showed an improved inter-rater correlation coefficient (ICC=0.82 for simulation vs. 0.65 for expert rating) for estimating the trunk flexion angle (Lu et al., 2009). Figure 3 shows posture specification errors between the simulation and observational methods. As seen in Figure 3, the accuracy levels of simulating mannequin postures and expert rating are comparable, while the accuracy of simulating self postures increases by an average 5°. The finding suggests that simulating self posture or a worker's posture in similar type may result in a significant decrease in posture specification errors by approximately 50%. A recent study has shown an average 9° error in estimating workers' trunk flexion angle on the sagittal plane (i.e. side view) for a variety of lifting tasks using the manual posture specification on the computer screen (Xu et al., 2011). It is worth noting that the 9° error falls in between the 6° and 12° errors in simulating self and mannequin postures in our studies.

Results from three experiments in Figure 3 (simulating self-posture, mannequin posture and rating by professional ergonomists) suggest the same trend that estimating an increased trunk flexion angle was associated with an increased estimation error. The finding is in line with several studies where increased errors in estimating shoulder and wrist posture were associated with an increased targeted angle (Genaidy, 1993; Lowe, 2008). Table 2 and 3 indicate that for the posture simulation method, the error trend applied to both trunk lateral bending and flexion. The reason that the trunk axial rotation error was not associated with the increased trunk flexion angle might be attributed to the relatively smaller trunk axial rotation angles for the trunk flexion group A (increased trunk flexion group). The trunk axial rotation angles for trunk flexion group A were 3° –27°, while the angles for the other two groups ranged from 0–45°. Caution should be exercised when using the subjective rating or the human posture simulation method to estimate an increased trunk flexion angle for postural risk assessments.

Results from the phase 2 experiment show that the mean of the simulation errors in trunk flexion, lateral bending and axial rotation angles ranged from 4° to 18° for the three groups of trunk flexion and 8° –16° for the three viewing angles. The results about estimating the three important postural risk factors for LBDs are not entirely satisfactory but perhaps tolerable for epidemiological research. If the simulator's body type is a match or similar in terms of height, weight and gender to the person in the video for assessment, the posture simulation method may offer a promising approach for a fairly accurate estimation of these trunk posture variables, as indicated by an improved average 6° simulation error for a variety of trunk postures in different views in the phase 1 experiment.

Among the three viewing angles, the side viewing angle had the least average errors for estimating both self's and mannequin's body posture angles. According to the correlation analysis (Table 4), the estimated back compressive force and moment data for the side viewing angle was also found to have the strongest correlation (r > 0.9) with both self's and mannequin's. This increased correlation for the side viewing angle seemingly was the results of the decreased average posture simulation error with this viewing angle. Therefore, to improve the accuracy of estimating the back compressive force and moment using the human posture simulation method, the side viewing angle is recommended.

With the limited sample size used in the experiment phase 2, it is difficult to conclude an under- or over-estimation of the back compressive force and moment using the human posture simulation method. According to the regression coefficients of the regression analysis for the five subjects, only one subject had a regression coefficient greater than 1. Most subjects had a coefficient ranging from 0.95–1. Therefore, the human posture simulation method appears to have a trend of underestimating both back compressive force and moment within a range of 5%.

As the level of hand load increased, the correlation between simulation and mannequin data decreased, indicating a compromised accuracy of estimating back compressive force and moment at an increased level of hand load. The decreased correlation is attributed to the multiplication effect of the horizontal moment arm from the load to the L4/L5 and hand load for calculating both force and moment data (Chaffin et al., 1999). This limitation may not be critical when one is to assess the biomechanical model driven back compressive force and moment for small to median hand loads.

As can be seen in Figure 2, the main advantage of the posture simulation method is its efficiency in completing posture specification of the 15 body angles. Previously, we reported an average time period of 20 sec to complete one posture simulation trial (Lu et al., 2011). The time was based on the preparation time and actual posture posing time (standardized 3 sec) without considering the time for presenting the posture on the screen and time for saving data to the computer hard drive by the computer operator. Taking these extra factors into account, the average time (~1.5 min) for each simulation trial is about 5 min less than manual posture matching on computer screen in the current study. Due to the limited data (one subject's 54 trials) we collected for assessing the efficiency of the on-screen posture matching method, the comparison does not seem generalizable. However, the time required for completing one human posture simulation trial is on average 3 min less than the reported data for similar on-screen posture specification trials reported in previous studies (Liu et al., 1997; Xu et al., 2011). For a large scale epidemiological study involving measuring the whole body postures for many manual materials handling tasks, the human posture simulation method may offer an efficient, precise and reasonably accurate way.

Our human posture simulation method has two advantages over on-screen manual posture matching methods. First, the human posture simulation method has the capability of specifying many body angles of interest at once, as compared to judging one angle at a time on the computer screen using the manual posture matching methods. This advantage leads to a significant reduction in labor and analysis time required by the on-screen methods. Second, human posture simulation has the capability of linking many body angles realistically, as compared to specifying one body angle at a time without considering anatomical limitations between the body angle being specified and other body angles using the on-screen methods. For example, excess trunk axial rotation typically comes with pelvic rotation in the same direction, resulting in a reduction in the trunk twisting or axial rotation angle with respect to the pelvis (Anderson et al., 1986). This reduction is difficult to take into account during manual posture matching on the computer screen and typically is not addressed by researchers. In 3DSSPP, a body linkage constraint algorithm is implemented to limit unrealistic manual posture specification; however, this constraint algorithm is based on range of motion data and is relatively unrealistic for most lifting situations, compared to human posture simulation that employs a real human body composed of natural constraints from muscles, bones, ligaments and soft tissues.

The study methodology has some limitations that warrant considerations. First, the small sample sizes for both experiments provide limited generality. Although statistically significant differences were found for the average posture simulation error in both experiments, the non-significant associations between test conditions (viewing angle, lift asymmetry and simulated trunk flexion angle) and some trunk posture simulation errors may raise a question about the appropriate sample size for assessing the simulation errors in these trunk posture variables. Post hoc power sample size calculations were performed to estimate the required sample sizes for the non-significant trunk posture variables for both experiments. To detect a significant difference ($p<0.05$ with power=0.9) in the accuracy of simulating the trunk lateral bending, axial rotation and flexion variables in the test conditions in the phase 1 experiment, a minimal sample size of 19, 26 and 41 was required, respectively. For the same trunk variables with the same statistical power in the phase 2 experiment, a minimal sample size of 13, 21 and 14 was needed, respectively. Research with a larger sample size is recommended to provide further data to quantify the human posture simulation errors. Second, theoretically, the simulation error for each posture variable may be influenced by relevant posture variables. For example, the simulation error for trunk axial rotation may be affected by the simulation error for trunk flexion because of the anatomical link. However, the interactions between the simulation errors for the 15 body posture variables were not assessed in both experiments. Due to the limited sample size, an assessment of the complicated interaction terms may not justify meaningful results. A preliminary analysis of linear correlation between the trunk posture simulation errors revealed that the correlation coefficients varied from 0.2–0.3 for both experiments. The poor correlations imply the complicated hypothesized interactions that may warrant further investigations. Third, the computer generated mannequin posture was not realistic; however, to investigate the effects of simulation errors on the accuracy of estimating the back compressive force and moment by the posture simulation method, it was perhaps the most accurate method for comparisons. The resolution of the mannequin for rendering a realistic human figure should have sufficient details for posture specification, as presented in Table 1. In addition, the use of the mannequin as a realistic person completely eliminated the probabilities of measurement errors using a person's posture data recorded by the motion capture system. Using a real person's data for comparisons may also raise a question about the unknown effects of personal body characteristics, such as body type, size and height. Due to the number of trials to be completed during the test session, these personal factors were difficult to investigate simultaneously with the studied factors (viewing angle, trunk flexion level and lift asymmetry). Nevertheless, future research on the additional factors is recommended to further validate the applications of the method.

While direct-reading measurement tools for physical risk quantifications are not well developed for field use, the human posture simulation method offers a novel approach to quantifying postural stress and biomechanical measures in the workplace. Since the method is based on the premise that biomechanical measures are associated with the development of LBDs, the value of the method in correlating the biomechanical variables with health outcomes has yet to be evaluated.

5. Conclusions

It is possible to use the human posture simulation method to simultaneously estimate multiple body angles from field recorded video. The method enables researchers to determine postural risks for musculoskeletal disorders and calculate spinal loading variables with accuracy and precision comparable to on-screen posture matching methods. The efficiency of this method presents the main advantage over the traditional on-screen posture matching approaches. The disadvantage of the method is initial costs and training required for using a motion capture system for human posture simulation.

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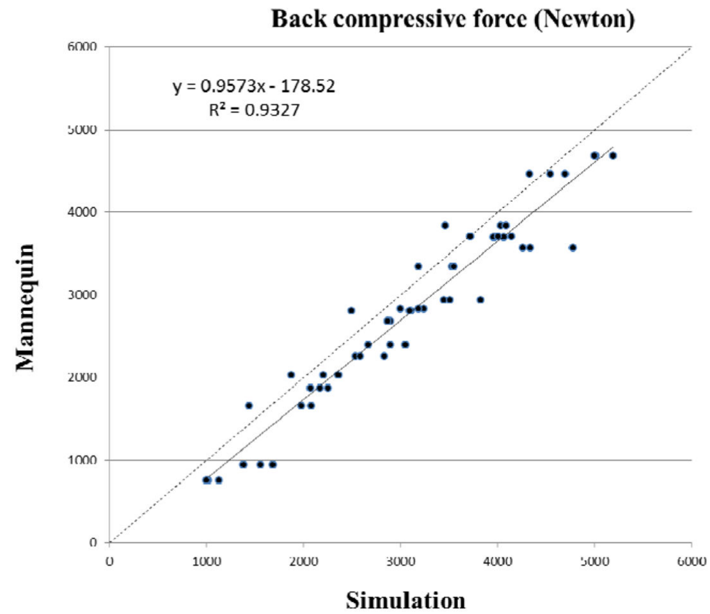
(A)



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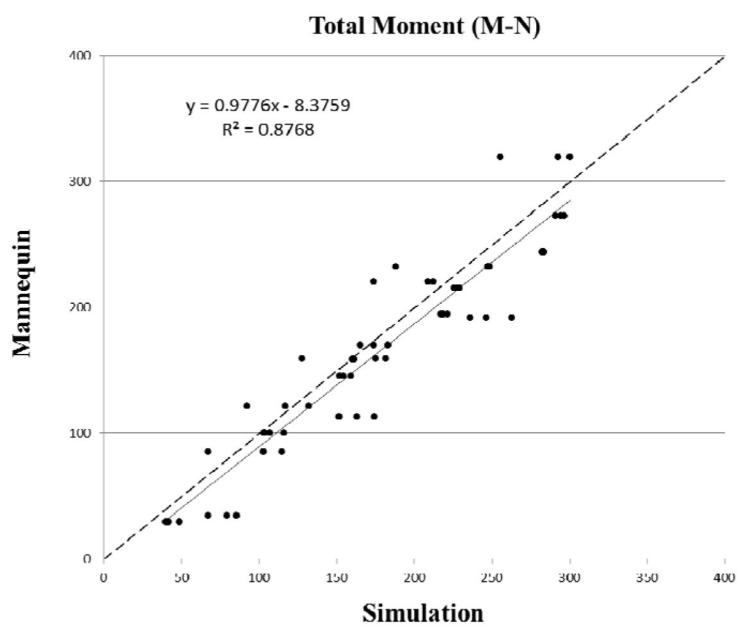

Figure 1.

Linear regression lines (solid) predicting the back compressive force (A) and total moment (B) at the L4/L5 intervertebral disc using simulation data for 54 lifting conditions (data from one subject). The dotted lines are diagonal lines.

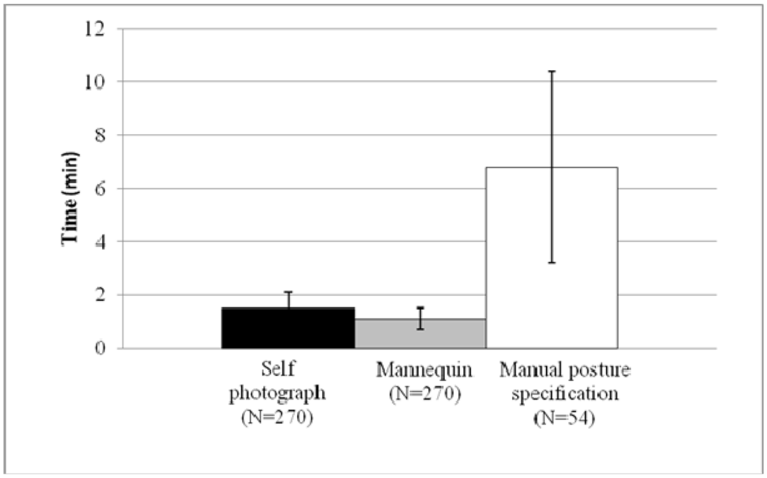

Figure 2.
Efficiencies of human posture simulation and manual on-screen posture matching methods (N represents number of trials)

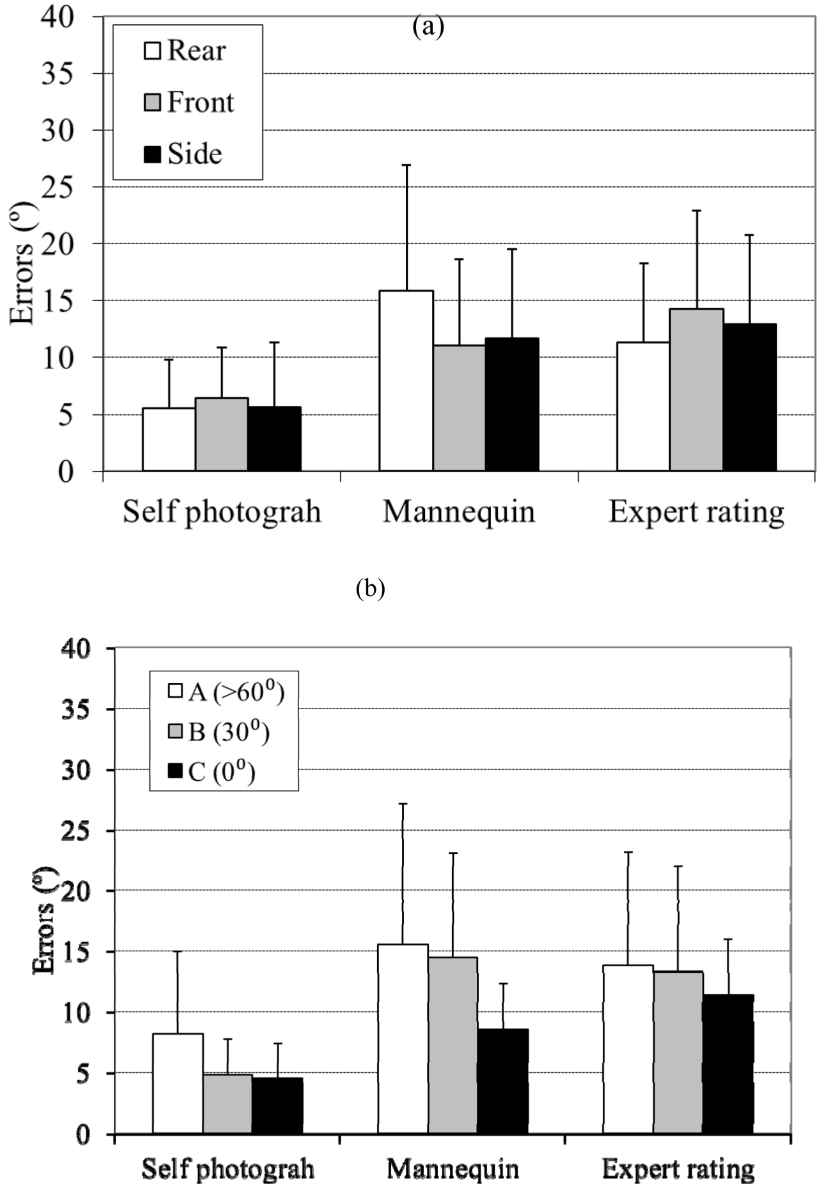

Figure 3.

Comparisons of errors (mean and SD) in estimating trunk flexion angle as a function of viewing angle (a) and simulated trunk flexion angle (b) between human posture simulation method (self and mannequin postures) and on-screen posture matching method (N=5)

Table 1

Characteristics of simulated postures (three levels of trunk flexion angle, two levels of lift asymmetry and three viewing angles)

	Front	Side	Rear	Trunk flexion	Lift asymmetry
1				75° (A)	45° (Yes)
2				60° (A)	0° (No)
3				30° (B)	0° (No)
4				30° (B)	45° (Yes)

	Front	Side	Rear	Trunk flexion	Lift asymmetry
5				0° (C)	0° (No)
6				0° (C)	45° (Yes)

Table 2

Posture simulation accuracy and precision measures as a function of viewing angle and trunk flexion angle (phase 1 experiment).

Phase 1 Experiment	Viewing angle (n=48) Mean (SD)			Simulated trunk flexion group (n=48) Mean (SD)		
	Rear	Front	Side	A (>60°)	B (30°)	C (0°)
Average postural simulation error (°)	12.0 ^{a} (4.7)	12.8^{a} (4.8)	11.0^{b} (5.1)	15.4^{a} (4.9)	9.9^{b} (3.8)	10.4 ^{b} (4.0)
Trunk lateral bending error (°)	6.5 (6.2)	6.1 (6.0)	7.4 (6.3)	11.1^{a} (8.3)	4.5^{b} (3.0)	4.3 ^{b} (2.5)
Trunk flexion error (°)	5.5 (4.3)	6.4 (4.5)	5.6 (5.7)	8.2 (6.8)	4.8 (3.0)	4.5 (2.9)
Trunk axial rotation error (°)	4.2 (2.3)	5.3 (3.8)	5.5 (4.2)	4.7 (3.4)	4.7 (3.0)	5.6 (4.2)
Average precision (°)	2.3 (2.2)	2.5 (2.1)	1.9 (2.5)	2.7^{a} (2.4)	2.4^{a} (2.6)	1.5 b (1.4)

[a, b, c] Different superscript letters represent a significant difference, P<0.05.

Table 3

Posture simulation accuracy and precision measures as a function of viewing angle and trunk flexion angle (phase 2 experiment).

Phase 1 Experiment	Viewing angle (n=30)			Simulated trunk flexion group (n=30)		
	Mean (SD)			Mean (SD)		
	Rear	Front	Side	A (>60°)	B (30°)	C (0°)
Average postural simulation error (°)	17.3 ^{a} (5.0)	14.3^{b} (4.5)	13.6^{b} (4.4)	17.0^{a} (4.1)	15.5^{a} (4.9)	12.8^{b} (4.7)
Trunk lateral bending error (°)	8.3 (5.8)	7.5 (5.1)	8.1 (5.3)	12.7^{a} (5.5)	7.1^{a} (3.4)	4.1 ^{b} (2.6)
Trunk flexion error (°)	15.9 (11.0)	11.1 (7.5)	11.7 (7.8)	15.6 (11.6)	14.5 (8.6)	8.6 (3.8)
Trunk axial rotation error (°)	13.7 (11.2)	13.7 (11.1)	14.3 (11.1)	7.6^{a} (4.6)	18.1^{b} (9.8)	16.0 ^{c} (13.8)
Average precision (°)	2.7 ^{a} (2.2)	1.4^{b} (1.1)	1.5^{b} (1.3)	2.2 (2.1)	1.9 (1.7)	1.6 (1.1)

$^{a, b, c}$Different superscript letters represent a significant difference, P<0.05.

Table 4

Mean values of correlation coefficients between simulation and mannequin data (A: back compressive force; B: moment) as a function of viewing angle and hand load (p-values for statistical significance of all correlation coefficients are <0.001).

A: Back compressive force

View	Hand load (kg)			Mean
	1.8	14.6	27.2	
Rear	0.93	0.85	0.79	0.86
Front	0.84	0.68	0.6	0.71
Side	0.95	0.9	0.84	0.90
Mean	0.91	0.81	0.74	0.82

B: Moment

View	Hand load (kg)			Mean
	1.8	14.6	27.2	
Rear	0.92	0.83	0.71	0.82
Front	0.86	0.69	0.56	0.70
Side	0.95	0.92	0.9	0.92
Mean	0.91	0.81	0.72	0.82